Appl. Phys. B 47, 187–190 (1988)

Applied Physics B Photophysics and Laser Chemistry

© Springer-Verlag 1988

Near Infrared Lasing Transitions in Ar, Kr, and Xe Atoms Pumped by a Coaxial e-Beam

P. J. M. Peters, Mei Qi-Chu*, and W. J. Witteman

Physics Department, University of Twente, NL-7500 AE Enschede, The Netherlands

Received 27 April 1988/Accepted 4 May 1988

Abstract. Optimizations of gas composition and input energy were performed for gas mixtures containing a buffer gas and either Ar, Kr or Xe as the lasing gas. The total gas pressure was varied between 1 and 14 bar and the input energy from 0.03 to 0.7 J/cm^3. The excitation source was a small coaxial electron beam with a pumping length of 20 cm and a pulse length of 30 ns (FWHM). From an active volume of 13.3 cm^3 a maximum output energy of 12 mJ was obtained from a gas mixture containing 0.3% Xe in Ar at a total gas pressure of 10 bar. The intrinsic efficiency was 0.9%.

PACS: 42.55 FN, 41.80 Dd

Atomic rare gas lasers have been known from the very beginning of laser physics. It was shown in 1963 that a high gain is possible in a tube filled with Xe at a low pressure [1]. A decade later the pulsed atomic rare gas lasers gained attention again as it was shown that they could work at atmospheric pressures as well [2–4]. Recently Basov et al. [5] reported a total efficiency of over 3% for an Ar:Xe laser pumped by a long pulse e-beam sustained system at a total gas pressure of 3.5 bar. In this paper we will report on optimization experiments with respect to the gas composition and pumping conditions at a high total gas pressure. The gas pressure could be varied between 1 and 14 bar. Each gas mixture contained a low content of either Ar, Kr, and Xe as the lasing gas diluted in either Ar, Ne or He as a buffer gas. To our knowledge only Chapovsky et al. [4] worked at such a high pressure but in a capacitively coupled discharge system. Our results are, however, an order of magnitude better.

1. Experimental Configuration

The laser gas was excited by a small coaxial electron beam apparatus [6]. The maximum diode voltage was about 300 kV with a peak diode current of 7.5 kA in a pulse with a length of 30 ns (FWHM).

The anode tube with a wall thickness of either 25 or 50 μm is made out of titanium. The inner diameter is 9.2 mm and the laser gas inside the tube is irradiated by the electrons over a length of 20 cm resulting in an active volume of 13.3 cm^3. The length of the resonator was 400 mm and it consisted of a gold coated total reflector with a radius of curvature of 2 m on one side, and a partial reflecting mirror on the other side. The output energy was measured with a Laser Precision RJP 734, 735 – RJ 7000 combination. The spectral composition was studied by means of a Hilger & Watts monochromator with a focal length of 30 cm and equipped with a 150 l/mm grating blazed at 4 μm. The outcoming signal was detected by a uncooled InSb (ORP-10) detector.

2. Experimental Results

2.1. Ar:Xe *Gas Mixture*

In order to estimate the intrinsic efficiency (which is defined as the ratio of the output laser energy and the input energy deposited in the gas) the energy deposition was measured by the pressure-jump method. This method was described already in an earlier paper [6]. In that paper the results are presented for the energy deposition in the gas for the case where a titanium tube with a wall thickness of 50 μm is used as anode. In Fig. 1 the results are plotted for a total gas pressure up to 10 bar. All numbers in the figure are

* Present address: Institute of Electronics, Academia Sinica, Beijing, People's Republic of China

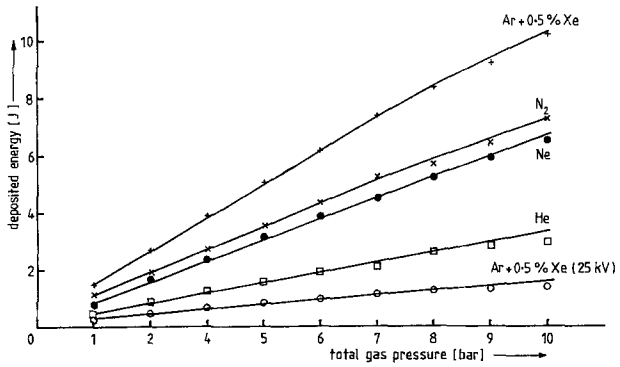

Fig. 1. Energy deposition of the electron beam in a volume of 16 cm^3 using a titanium anode with a wall thickness of 25 μm. The Marx load voltage was 60 kV for the upper four curves

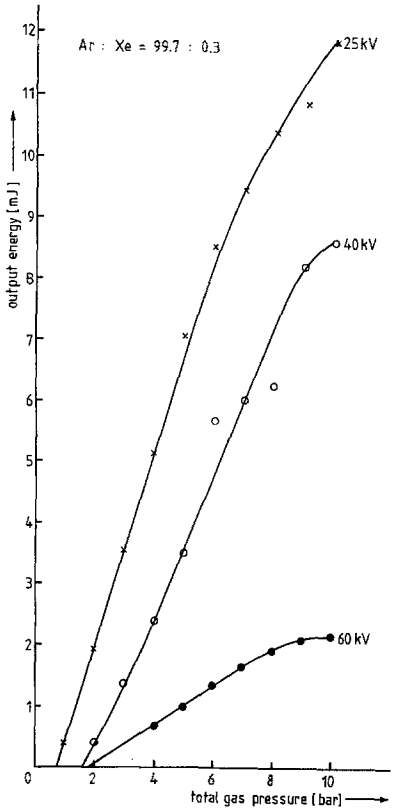

Fig. 2. Output energy as a function of the total gas pressure for different Marx load voltages (anode 25 μm Ti)

obtained using a titanium anode tube with a wall thickness of 25 μm. Compared to the results obtained with the 50 μm tube an increase in energy deposition of almost 100% was measured by using the thinner 25 μm anode tube. This tube however, had a pressure limit of 10 bar. For an Ar based laser gas mixture it can be seen that the energy deposition varies from about 90 J/l at a pressure of 1 bar to 625 J/l at the highest pressure of 10 bar.

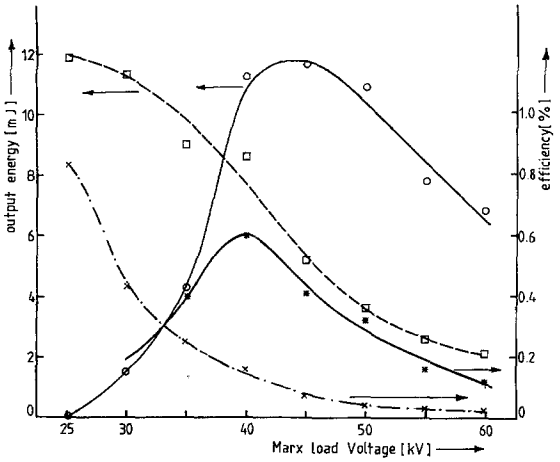

Fig. 3. Output energy and efficiency versus the Marx load voltage for two anode configurations. The dashed lines refer to a configuration with an anode thickness of 25 μm, the other ones to a 50 μm tube

The amount of Xe in an Ar:Xe atomic rare gas laser has been varied over more than an order of magnitude in several studies. We also started by finding the optimum Ar:Xe ratio for the laser gas mixture in our system. We found the highest output energy with a mixture of 0.3% Xe in Ar. There was no sharp peaked optimum. By taking the amount of Xe 5 times larger or 5 times smaller the output energy was still half the value of the maximum. We also estimated the optimum output coupling to be 50%.

During the experiments it appeared that the highest output energy was not obtained at the highest pumping density. By reducing the e-beam voltage (and current) the laser output energy was increased. The configuration with an anode tube with a wall thickness of 50 μm yielded an optimum output energy of slightly more than 12 mJ for a Marx load voltage of 45 kV. Earlier we obtained at a load voltage of 60 kV about 8 mJ from the same gas mixture [7].

More pronounced was the difference when we used the tinner anode tube of 25 μm wall thickness. In Fig. 2 the influence of the pump intensity on the laser output is plotted. We see a very strong dependency on the e-beam voltage. The numbers in the figure denote the charging voltages of the ten stage Marx generator. It should be remembered that not only the diode voltage but also the diode current changes when a different load voltage is applied to the Marx generator. From the figure we see that again an output energy of 12 mJ is obtained but now at a load voltage of 25 kV. Calculating the intrinsic efficiency we see a dramatic increase from 0.02% to 0.85% by taking a load voltage of 25 kV instead of 60 kV.

In Fig. 3 the efficiency and the output energy is plotted as a function of the Marx load voltage for a

total laser gas pressure of 12 bar inside a 50 μm thick anode tube and for a total pressure of 10 bar in a 25 μm tube. Looking at the efficiency one optimum can be seen around 40–45 kV for the 50 μm thick anode tube while a second one for the thinner (25 μm) tube can be estimated at 20–25 kV.

From the energy deposition measurements as a function of the Marx load voltage we know that for the 25 μm anode tube energy deposition started at about 17 kV. For the thicker (50 μm) tube this threshold voltage was about 27 kV. The maximum efficiency is obtained for a rather low input energy (1–2 J/16 cm^3). From Fig. 3 it can be seen that the efficiency decreases very fast if the energy input or the pumping density exceeds these low value.

2.2. He:Xe, He:Kr, *and* He:Ar

After optimisation of the Ar:Xe gas mixture we studied the behaviour of other buffer gases, first with Xe then with Kr and Ar. Starting from the optimum Ar:Xe mixture we replaced step by step Ar by Ne as the buffer gas. The output energy measurements show that the laser operates less efficiently as more and more Ne is used. In Fig. 4 the influence of adding Ne to a He-based gas mixture is shown for an atomic Xe laser. The deleterious effect of Ne with respect to the laser output is manifest. A gas mixture with pure Ne and 0.3% Xe yields only 0.6 mJ of output energy at a total gas pressure of 14 bar. By replacing the Ar step by step by He (containing 0.3% Xe in the gas mixture) the output energy also decreased but not as strongly as with Ne. At a total gas pressure of 14 bar the output energy was about 2.5 mJ when all Ar was replaced by He. From the energy deposition measurements it is known that compared to Ar in He about one third of the energy is deposited at the same gas pressure. This means that the intrinsic efficiency of the He:Xe laser is only slightly lower than the efficiency of the Ar:Xe laser. We therefore studied in more detail the behaviour of Xe, Kr, and Ar as the lasing species, with He as the buffer gas. First the optimum concentration of Xe, Kr or Ar was estimated. A typical example is given in Fig. 5 for a He:Kr laser gas mixture. The output energy increased almost linearly with the total gas pressure up to 10 bar. Gas mixtures containing an amount of Xe, Kr or Ar well above the optimum concentration saturated at a somewhat lower pressure of around 8–9 bar. It is clearly shown by our measurements that the saturation did not start at a pressure of about 4 bar as is stated in a paper by Basov et al. [8]. The estimated optimum gas composition of the three different lasers contained about 0.1% of either Xe or Kr and about 0.4% of Ar diluted in He as the buffer gas. Optimisation of the output energy with respect to the gas composition was

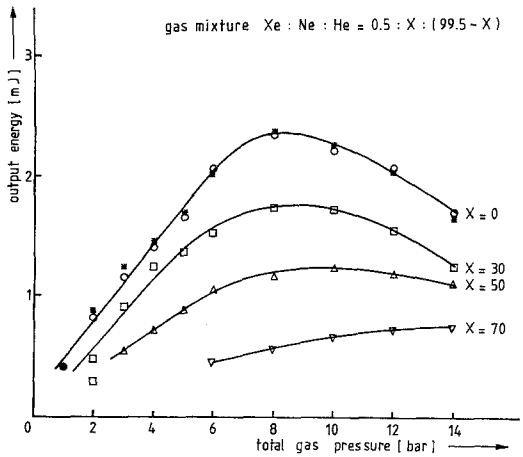

Fig. 4. The dependency of the output energy on the Ne concentration as a function of the total gas pressure ($V_{load} = 60$ kV)

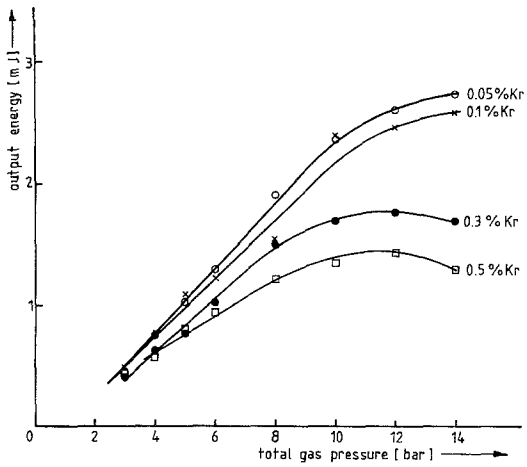

Fig. 5. Output energy as a function of the total gas pressure for various concentrations of Kr in He. The Marx load voltage was 60 kV

carried out by using a tube with a wall thickness of 25 μm as well as the 50 μm tube as anode.

With the 50 μm tube the output energy of the optimized He:Xe, He:Kr, and He:Ar mixtures at a total pressure of 14 bar started at a Marx load voltage of 30 kV, and increased linearly with the voltage (or the pumping power) to about 2.5 mJ at the maximum load voltage of 60 kV. For the same mixtures at a total gas pressure of 9 bar inside the 25 μm anode tube the output energy increased linearly with the load voltage up to 40 kV and then saturated to almost constant values of about 2.2 mJ.

3. Discussion

Studying the role of the buffer gases in atomic rare gas lasers it appeared that the results with He as the buffer gas were comparable with the ones of Ar keeping in

Table 1. Wavelengths measured for different gas mixtures

	Wavelength [μm]				
He:Ar	1.79				
He:Kr	2.52	3.07			
He:Xe	2.03	2.65	3.65		
Ar:Xe	1.73	2.03	2.63	2.65	3.37

mind the lower stopping power of He. In contrast Ne produced inferior results; the use of Ne was deleterious for these type of lasers. Apparently the energy transfer from Ne^+ to the active rare gas (Xe, Kr or Ar) is different compared to Ar and He. It is known that the rate constants of the charge transfer processes from Ne_2^+ to Xe^+ or to $NeXe^+$ are three orders of magnitude smaller than the ones of Ar_2^+ and He_2^+ [9].

Moreover there is some evidence that the recombination of $NeXe^+$ yields Xe* in the lower 6*p* laser level [8]. This 6*p* level is also filled by the recombination reaction of Xe_2^+ which accounts for the decrease in laser output for higher Xe concentrations at high total gas pressures. The experiments showed also very clearly that the energy input should be in the order of 1 J/16 cm^3 (2 MW/cm^3). Under more intense pumping conditions the output energy and the efficiency decreased rapidly. Probably the increase in secondary electrons in the plasma as a consequence of the higher pumping power changes the kinetics in an unfavourable way. Spectroscopic details will be presented in another paper but the main wavelengths obtained with this system are given in Table 1.

Acknowledgement. This experiment was partially supported by the Dutch "Stichting voor Fundamenteel Onderzoek der Materie".

References

1. W.B. Bridges: Appl. Phys. Lett. **3**, 45 (1963)
2. O.R. Wood, E.G. Burkhardt, M.A. Pollack, T.J. Bridges: Appl. Phys. Lett. **18**, 261 (1971)
3. S.A. Lawton, J.B. Richards, L.A. Newman, L. Specht, T.A. de Temple: J. Appl. Phys. **50**, 3888 (1979)
4. P.L. Chapovsky, V.N. Lisitsyn, A.R. Sorokin: Opt. Commun. **16**, 33 (1976)
5. N.G. Basov, W.V. Baranov, A.Y. Chugunov, V.A. Danilychev, A.Y. Dudin, I.V. Kholin, N.N. Ustinovskii, D.A. Zayarnyi: IEEE J. QE-**21**, 1756 (1985)
6. P.J.M. Peters, I.H.T. Fierkens, W.J. Witteman: Appl. Phys. Lett. **51**, 883 (1987)
7. P.J.M. Peters, H.M.J. Bastiaens, W.J. Witteman: Proc. CLEO, 160, 1987, Baltimore (USA) Paper WI37
8. N.G. Basov, V.V. Baranov, V.A. Danilychev, A.Yu. Dudin, D.A. Zayarnyi, L.V. Semenova, N.N. Ustinovskii, I.V. Kholin, A.Yu. Chugunov: Sov. J. QE-**16**, 320 (1986)
9. D.K. Bohme, N.G. Adams, M. Mosesman, D.B. Dunkin, E.E. Ferguson: J. Chem. Phys. **52**, 5094 (1970)